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HIERARCHICAL STRUCTURES AND STRENGTH IN COLD-DRAWN PEARLITIC STEEL WIRE

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ABSTRACT

Deformation, as one of the major methods to improve the (specific) strength of metals, can be combined with phase transformation to improve the strength of nanometals to an ultrahigh level close to the theoretical strength in single crystals. This is demonstrated by the analysis of the microstructural evolution, strengthening mechanisms and strength–structure relationships in a cold-drawn pearlitic steel with a structural scale in the nanometer range and a flow stress up to about 3.5 GPa. Structural parameters including the interlamellar spacing, the dislocation density in the ferrite lamellae and the cementite decomposition, have been analyzed and quantified by scanning electron microscopy, transmission electron microscopy and high resolution electron microscopy for wires cold drawn up to a strain of 3.68. Three strengthening mechanisms, boundary strengthening, dislocation strengthening and solid solution hardening, have been analyzed based on the microstructural analysis. The individual and combined contributions, of these mechanisms to the wire strength have been estimated and good agreement has been found between the measured flow stress and values estimated based on an assumption of linear additivity of the three strengthening mechanisms. Mechanisms behind the higher strength of about 6.4 GPa in the wires drawn to higher strains and to a finer microstructural scale is also discussed.

1. INTRODUCTION

There are many ways to improve the strength of steels and examples are phase transformation, plastic deformation and a combination of these methods (Tsuji and Maki 2009). By phase transformation strong bainitic and martensitic steels can be produced (Christian 2002; Bhadeshia 2010). Very strong steels can also be produced by plastic deformation to very high strain but drawbacks are the large working force required and the poor formability of deformed product be maintained at very high strains where the cementite between neighboring ferrite lamellae totally dissolves leaving behind LAB/HAB interfaces between neighboring ferrite lamellae with a high concentration of carbon. At the same time dislocation strengthening shows no saturation, which suggests that dislocations continuously contribute to the stress also at very large strain. For the solid solution hardening, the contribution is most difficult to quantify as it not only depends on the solubility of carbon in the ferrite matrix but also depends on an interaction with dislocations. These problems are, however, for future research as it involves not only characterization of the cementite, the cementite – ferrite interface / ferrite – ferrite interface and crystallographic rotation of neighboring ferrite lamellae which may enhance the interfacial resistance to glide, but also the distribution of dislocations, dislocation boundary formation in the thin ferrite lamellae, and of carbon atom distribution including those in solution. Such characterizations may require not only the more advanced techniques and/or the combination of these techniques such as three dimensional atom probe tomography (3DAPT) and chemical mapping and quantification at the atomic scale by scanning transmission electron microscopy (STEM), but also the combination with advanced modeling such as the molecular dynamics and first-principles calculations based on density functional theory (DFT) (Xu and Zhang 2014).

At the same time, further optimization of the strong wires will be carried out from both technological and scientific points of view. From the technological viewpoint, the optimization of ductility can be achieved by heat treatment and the further improvement of strength may be obtained by chemical composition adjustment and by altering the deformation route for example by combining rotary swaging and drawing. From the scientific viewpoint, in-situ TEM deformation of these strong wires may also give new input for the understanding and design of strong multiphase structures.

6. CONCLUSIONS

The microstructure, strengthening mechanisms and strength–structure relationships have been analyzed in a cold-drawn pearlitic steel with a flow stress about 3.5 GPa, and extrapolated to the higher strains with a flow stress up to 6.4 GPa. Structural parameters including the interlamellar spacing, dislocation density in the ferrite lamellae and the cementite decomposition, have been analysed, quantified by transmission electron microscopy and high resolution electron microscopy and/or extrapolated for wires cold drawn up to a strain of 6.02. The conclusions are as follows:

1. The structural evolution is hierarchical as the structural variations have their causes in a different macroscopic orientation of the cementite in the initial (patented) structure with respect to the wire axis. The through-diameter variations subdivide the lamellar structure into two types A_A and A_BC where the latter has larger interlamellar spacings and larger misorientation angles both along and across the lamellae. In both A_A and A_BC structures the dislocations are stored as individual dislocations and in low angle cell or subgrain boundaries.

2. The interlamellar spacing and the thickness of the cementite lamellae are reduced in accordance with the changes in wire diameter up to a strain of 2.5. At higher strains enhanced thinning of the cementite lamellae points to decomposition of the cementite and carbon enrichment of the ferrite lamellae. Saturation in the thickness of ferrite lamellae is not observed. No saturation in the dislocation density is observed. The dislocation density increases to about 6×16 m^{-2} at a strain of about 6 and is supplemented with a high dislocation density at the ferrite/cementite interfaces.

3. Three strengthening mechanisms, boundary strengthening which increases with decreasing spacing between the cementite lamellae, dislocation strengthening which increases with the dislocation density in the ferrite lamellae and solid solution hardening which increases with carbon concentration in the ferrite lamellae have been analyzed based on the microstructural analysis. The individual and combined contributions, of these mechanisms to the wire strength have been estimated and good agreement has been found between the measured flow stress and values estimated based on an assumption of linear additivity of the three strengthening mechanisms up to a strain about 6 and a flow stress of 6.4 GPa. Saturation in the evolution of structure and strength has not been observed.

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